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Display-Control Compatibility in 3-D Displays 2: Effects of Cue Symmetry

A.W.F. Huggins and David J. Getty

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This report describes the second set of four experiments in a series of studies on display-control compatibility issues in a true volumetric display called SpaceGraph. As in the initial set of experiments, we measured the speed and accuracy of simple control decisions when the displayed object was presented in orientations rotated away from congruence with the control orientation. Reaction times were measured for identifying the marked face of a static

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cube, presented with SpaceGraph, as a function of how much the cube image was rotated away from congruence with fixed physical cube on which the observer responded, using orientation cues with various symmetries. The following results were obtained: (1) We confirmed the hypothesis derived from our initial experiments that responses cued by asymmetric aspects of the orientation cue are much faster than those cued by symmetric aspects of the cue;
(b) Consequently, significant reductions in display-control incompatibility were obtained by eliminating symmetries in the orientation cue, with the implication that, for example, aircraft icons in a true 3-D display should be deliberately made left-right asymmetric by marking the wings differently; and (c) performance continues to improve with experience over many thousands of trials.

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DISPLAY-CONTROL COMPATIBILITY IN 3-D DISPLAYS 2: EFFECTS OF CUE SYMMETRY

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1. INTRODUCTION

This report describes the second set of four experiments performed to investigate some of the difficulties human operators are likely to encounter in viewing and using abstract, volumetric, three-dimensional displays in practical applications. By an abstract display, we mean one in which the image is constructed, as opposed to being reproduced veridically, as in a TV image. Stereoscopic 3-D displays, consisting of a pair of 2-D images, can be either abstract or veridical in this sense. By a volumetric display, we mean one in which the (virtual) image viewed by the observer is space-filling: points in the image are at different depths from the observer. Vibrating mirror displays, exemplified by SpaceGraph™, belong to this class.

The initial set of four experiments, described in an earlier report (Huggins & Getty, 1981), studied how the speed and accuracy of responses in a choice reaction task were degraded as the orientation of the stimulus image varied relative to that of the fixed response array. The images were presented on a true volumetric 3-D display called SpaceGraph, that was developed at Bolt Beranek and Newman Inc (Sher, 1979; Sher, 1981). The second set of experiments, reported here, extend the results obtained in the earlier experiments by studying the effects of symmetry in the shape and position of the cue used to indicate the

orientation of the displayed object to the operator. The remainder of the report is organized as follows: first we describe briefly the SpaceGraph display, and summarize the results obtained in our first set of experiments, which we refer to throughout as Experiments 1-4. Then we describe the four experiments in the present set, which we refer to as Experiments 5-8 to avoid ambiguity. In Experiment 5, we tested our explanation of our earlier results in terms of the strategies available to the observers for selecting their responses. A modified orientation cue changed the relationships between responses and reaction time functions as predicted by our hypotheses. In Experiment 6, we modified the orientation cue in a different way, so as to eliminate the use of the least efficient strategy by ensuring that a more efficient strategy was always available. In Experiment 7, we used the same orientation cue as in Experiment 6, but applied it successfully to the most difficult task used in the initial set of experiments. Finally, in Experiment 8, we replicated exactly Experiment 1 of the initial set of four, to establish how much performance had improved as a result of prolonged exposure to the task.

1.1 SpaceGraph

The display used in the studies is a true space-filling

display called SpaceGraph. It differs from stereoscopic displays in that the image viewed by the observer is truly three-dimensional: virtual images of the luminous points from which the image is composed actually exist at different depths from the observer. This contrasts with stereoscopic displays, which attempt to recreate with two flat displays what the observer's left and right eyes _would_ see _if_ they were looking at a three-dimensional image.

Unfortunately, it is impossible to convey the immediacy and the conviction of the 3-D image except by viewing the live image: flat photographs and sketches of the images, such as appear in this report as illustrations, are highly ambiguous with respect to depth, because they incorporate _none_ of the cues that can be used to perceive depth, except for perspective.

Figure 1 shows a schematic view of the experimental apparatus, including SpaceGraph. SpaceGraph itself consists of a computer-controlled CRT, a circular vibrating mirror, and the computer that controls the CRT (not shown in the figure). The observer views the face of the CRT, reflected in the circular flexible mirror. The mirror is mounted on the front of a low-frequency loudspeaker. When the loudspeaker is excited by a 30 Hz sine wave, the mirror flexes, approximately spherically, cycling successively through flat, concave, flat, and convex

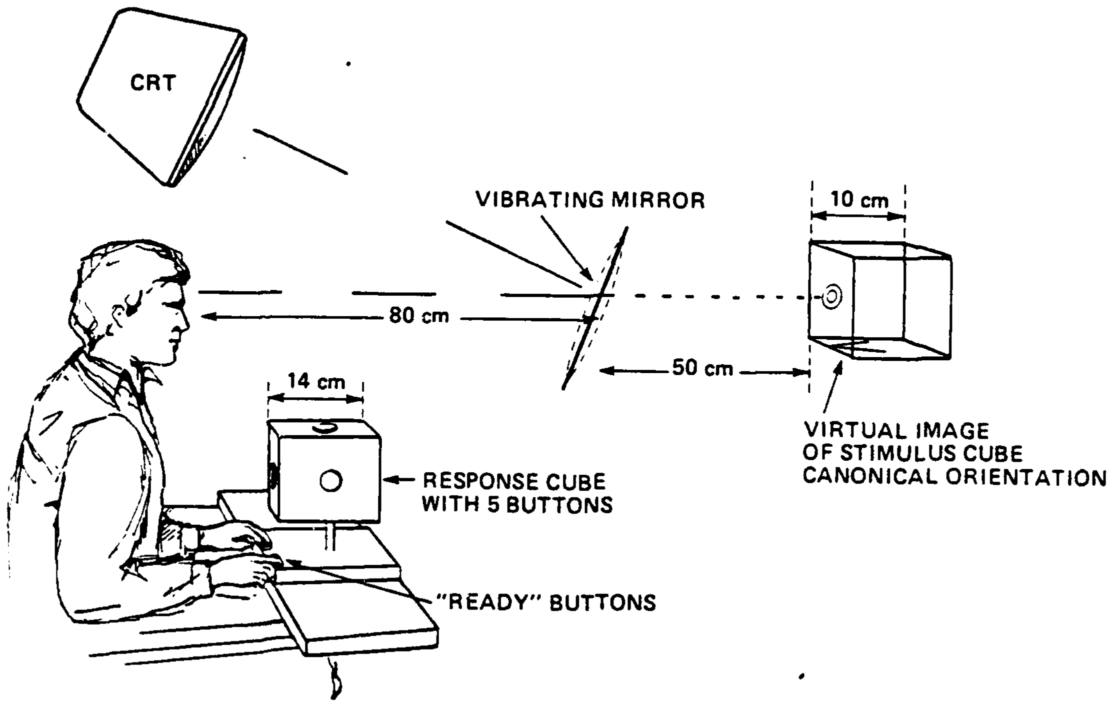

Figure 1. Sketch of observer with response box and SpaceGraph display. The observer viewed the CRT in a vibrating mirror, which generated a virtual image of the stimulus cube behind the mirror.

shapes 30 times per second. As it does so, the virtual image of the face of the CRT, which appears to the observer to be behind the mirror, sweeps cyclically through a depth of about 30 cm. If a point on the face of the CRT is momentarily brightened at the same instant in every mirror cycle, the observer will see a luminous point suspended at a specific depth in the dark void behind the mirror. The depth of the point can be varied by

changing the instant in the mirror cycle at which the CRT beam is unblanked. Thus the depth dimension of a point in the image is specified by the phase in each mirror cycle at which it is momentarily displayed. The lateral and vertical positions of the point can be varied by changing where on the face of the CRT the bright point is produced.

Images are built of points and linear arrays of points. In the prototype model on which we did our experiments, about 3000 points are available for drawing an image, corresponding to 300 cm of lines at 10 points per cm. This is sufficient for a fairly complex image.

Since the points comprising the image are truly at different depths from the observer, the image shows perspective distortion identical with that of a physical 3-D object. The binocular parallax effect, and the movement parallax effects that result from head movements by the observer, are real rather than simulated. In this respect, the image has some of the properties of a hologram. The observer's binocular viewpoint is not fixed, but can be moved laterally or vertically, or rotated about the line of sight -- and indeed the 3-D percept is enhanced by such movements. The amount of movement possible is constrained only by the requirement that the viewer not lose sight of the CRT face reflected in the mirror.

2. EXPERIMENTS ON ORIENTATION

Displays such as SpaceGraph will typically be used to present information about the relative position, orientation, and movement of vehicles, to permit an operator to make decisions relating to the control of one or more of them. In our initial set of studies (Huggins & Getty, 1981), we studied the identification of direction (up, down, left, right, etc.) for an object presented in an arbitrary orientation. We summarize these studies first, because the present studies used exactly the same procedures.

The experiments studied the effects on reaction time of varying the orientation in which a stimulus object, an outline cube, was presented. In each of the first three experiments, all the cube orientations seen by the observer were obtained by rotating the cube about one of its major axes: the vertical Y-axis in Experiment 1, the depth or Z-axis in Experiment 2, and the lateral X-axis in Experiment 3. In Experiment 4, rotations about any one of the three axes occurred in an unpredictable sequence.

In each experiment, the stimulus image consisted of an outline cube with sides about 12 cm long, that appeared to be behind the mirror and about 1.2 meters from the observer. The

orientation of the cube was indicated by a cue drawn on its bottom face, consisting of a capital letter V with its apex almost touching the front edge. One of the other five sides, chosen randomly on each trial of an experiment, was marked with a "stimulus button" consisting of two small concentric circles. The observer's task was to decide whether it was the top, left, right, near, or far face that was marked, and press the response key on the corresponding face of the fixed response cube in front of him (see Figure 1).

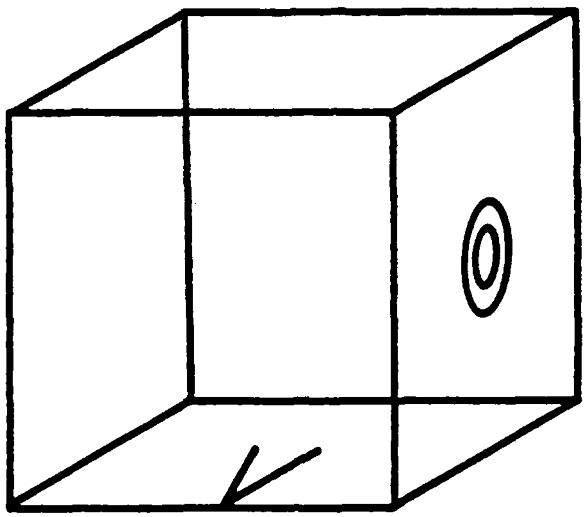

Figure 2. Schematic illustration of the appearance of the stimulus cube on a typical trial.

Figure 2 presents a _two-dimensional_ sketch of what the observer saw on a typical trial: in this example, the _front_ face

is nearest to the observer, and the right face of the cube is marked with the stimulus button. We stress that the sketch is two-dimensional, as are all the other illustrations in this report (for obvious reasons). It is important to keep in mind that all the images presented to the observers were truly three-dimensional, with none of the depth ambiguity seen in the figures.

In the first experiment, the cube could appear in any one of 24 different orientations, which together comprised a complete rotation of the cube image about its vertical Y-axis in 15 degree steps, starting at a "canonical" orientation rotated 10 degrees from the head-on orientation to avoid a problem inherent in SpaceGraph with drawing lines strictly parallel to the virtual image of the CRT face (Huggins & Getty, 1981).

On an individual trial, the observer might see the cube in any of the 24 orientations, and any one of the five buttons might be showing, yielding a total of 120 distinct stimulus arrays. Figure 3 is a negative made from a paste-up of 24 Polaroid photographs of the 24 orientations used in the experiment, except that the image for each orientation shows all five stimulus buttons to save space. The images seen by the observers consisted of bright points and lines hanging in a dark void.

Ignoring the fine-grain detail, the response-time functions

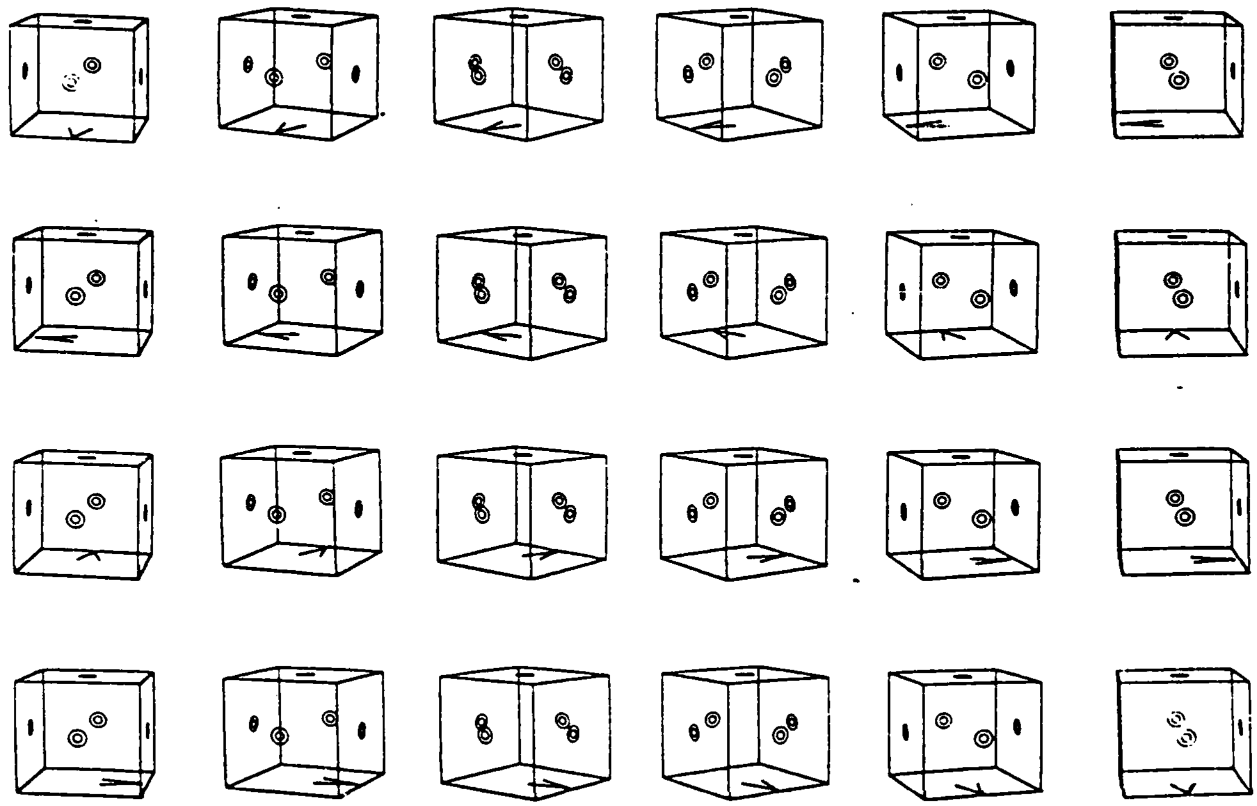

Figure 3. The 24 orientations of the stimulus cube used in Experiment 1 (Huggins & Getty, 1981), in which rotation was around the cube's vertical or Y-axis. All five stimulus "keys" are shown in each view, to save space. On each trial, the observer saw only one of the five stimulus keys.

fell into three distinct groups: fast, flat functions showing no effects of rotation; peak-shaped functions in which the response time increased almost linearly with rotation away from the head-on orientation; and plateau-shaped functions that began like the peak-shaped functions, but showed no further increases in response time with rotation beyond about 90 degrees from the head-on orientation.

We suggested the following explanations for the shapes of the three types of function. Observers use three main strategies to decide which of the cube's faces is marked. The fastest and easiest strategy is the Spatial strategy, which depends on a direct mapping from the displayed object to the control object. As a result, it can only be applied either when the cube appears in head-on orientation (for all keys), or, in an experiment involving rotation about a single axis, when the presented key lies on the axis of rotation and, consequently, does not change its position as the cube is rotated (for example the TOP key in the first experiment, with rotation about the vertical Y-axis). The second strategy is the Relational strategy. This depends upon an asymmetry in the cue used to mark the cube's orientation that can be used to distinguish between an otherwise confusable pair of stimuli (such as the NEAR and FAR keys). The third strategy is the Rotational strategy: the observer mentally rotates his viewpoint to a position from which the cube would appear in head-on orientation, at which point the Spatial strategy can be applied.

The Spatial strategy is always the fastest and most efficient, in the conditions under which it applies. The relative efficiency of the remaining two strategies varies with cube orientation: the Rotational strategy is more efficient than the Relational strategy near to the head-on orientation, when the

amount of mental rotation is small, but becomes rapidly less efficient as the amount of rotation increases beyond about 90 degrees. However, in conditions where neither the Spatial nor the Relational strategies can be applied (for example when a LEFT or RIGHT stimulus key is presented, and the cube is rotated more than 90 degrees away from the head-on orientation), the observer is forced to use the Rotational strategy even though it is very inefficient and yields very long reaction times. The foregoing description, together with some qualifications to account for details, accounts for all the results obtained in the first three experiments, each of which involved rotation about a single axis.

In the fourth experiment, rotation about any of the three axes might occur on a particular trial. The results obtained with mixed axes of rotation were very similar to those obtained in each of the single-axis experiments, with two exceptions. First, since the axis of rotation varied unpredictably from trial to trial, no stimulus key always lay on the axis of rotation. Therefore, the Spatial strategy could be applied only when the cube appeared close to head-on orientation. Secondly, observers had great difficulty in the mixed-axis task when the cube's orientation was reversed from head-on, especially when it was inverted. This was because the inverted orientation could be reached by rotation about either the lateral axis or about the depth axis, and these called for diametrically opposed responses.

The two rotations could be distinguished only by the orientation cue: when rotation was about the lateral axis, the V pointed away from the observer in the inverted orientation, whereas when rotation was about the depth axis, it pointed towards the observer. We will return to this below in Experiment 7.

3. EXPERIMENT 5

The first experiment in the present set, Experiment 5, was designed to test the foregoing explanation of the results of the initial set of experiments. If use of the Relational strategy depends on the symmetry of the cue used to mark the orientation of the cube, then the shape of the reaction time function for a particular response should depend on the symmetries of the particular orientation cue used, which can be manipulated. If this turns out to be true, it may then be possible to design an orientation cue that ensures that the operator always has a Relational strategy available to guide the choice of response, so that use of the inefficient Rotational strategy is not necessitated by lack of an alternative.

The "V" symbol chosen for Experiments 1-4 displayed left-right symmetry but not top-bottom symmetry. Furthermore, its position on the bottom face of the cube was symmetric with respect to the left and right faces, but asymmetric with respect to the front and back faces (that is, the V was placed between the middle of the bottom face and its NEAR edge). Thus two distinct relational strategies could be used for the NEAR and FAR responses, one based on the asymmetry of the <u>position</u> of the V and the other on the asymmetry of its <u>shape</u>. A further Relational strategy could have been used to select the TOP

response, since the TOP key always appeared on the face opposite the face bearing the V. This strategy would have depended only on the position of the V, and not on its shape. No relational strategy was possible for the LEFT or RIGHT responses, because the LEFT and RIGHT stimulus keys were placed symmetrically with respect to both the position and the shape of the V.

Had a different letter been chosen, such as an E or an F, or had the cue been placed left-right asymmetrically, then a relational strategy could have been used for these responses also. On the other hand, the choice of an E, with its up-down symmetry, would have prevented a relational strategy for the NEAR and FAR responses based on the shape of the letter, although one based on its position might still have been available. But these letters are very different in shape from the V used in the earlier experiments, which might have led to unexpected differences in results and thus complicated their interpretation. Therefore, for the first experiment in the present series, we chose an orientation cue whose symmetry was very similar to that of the V, without being so similar that experience in the earlier experiments would produce interference: an upper case A. Although the symmetry of an A is similar to that of the V, we changed both the orientation of the cue relative to the cube, and the position in which it appeared. The A was drawn on the bottom face of the cube as before, but with its feet almost touching the cube's left

edge. This has the effect of reversing the relationships in the earlier set of experiments between cue symmetry and the four stimulus keys on the sides of the cube. The shape and the position of the orientation cue are now asymmetric with respect to the LEFT and RIGHT stimulus keys, but symmetric with respect to the NEAR and FAR keys.

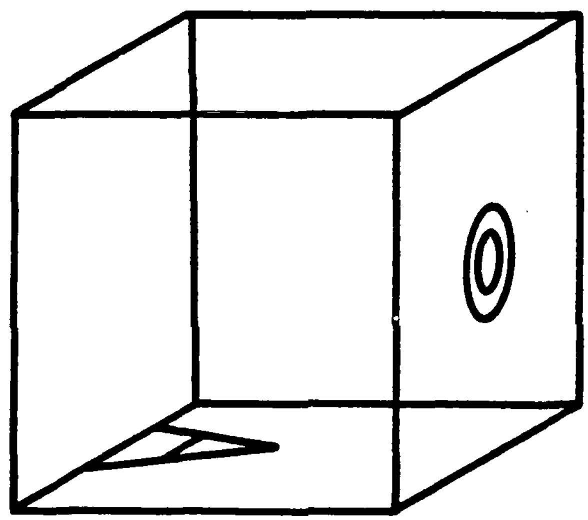

Figure 4. Schematic diagram of the stimulus cube for a typical trial. The orientation cue was a capital letter A with its base on the left edge of the bottom face. The RIGHT face of the stimulus cube is marked with a stimulus key.

Figure 4 is a schematic illustration of the stimulus cube as it might appear on a typical trial. The front of the cube is towards the observer, as before, and a stimulus key consisting of two small concentric circles is shown on the RIGHT face of the cube.

3.1 Method

The procedure used was identical to that in the earlier experiments, and used the same experimental apparatus as illustrated in Figure 1. The observer sat in a chair about 60 cm from the vibrating mirror, so that the line of sight to the center of the stimulus cube declined about 10 degrees below the horizontal. In front of the observer, mounted on a shelf, was a fixed metal response cube of side 15 cm, with a 5 cm diameter plexiglass key flush-mounted in the middle of each side except the bottom. To begin a trial, the observer pressed two "Ready" buttons mounted on the shelf on each side of the response cube, one with each hand. Two seconds later the stimulus cube appeared. The stimulus image consisted of 12 lines corresponding to the edges of the cube, each 12 cm long; the orientation cue, a capital letter A drawn on the bottom face, with its feet almost touching the left edge, and its apex almost at the center of the bottom face; and a stimulus key consisting of two small concentric circles that served to mark one of the remaining five faces. The cube image appeared in one of 24 orientations constituting a complete revolution around the cube's vertical Y-axis in 15 degree steps. Except for the different orientation cue, the stimuli were identical with those used in the earlier experiments, which were shown in Figure 3.

The observer held down the ready buttons while deciding <u>which</u> face of the stimulus cube was marked with a button, and then pressed the physical button on the corresponding face of the response cube. Observers were instructed to respond as fast as possible, while minimizing errors. To minimize the differences between the present experiment and the earlier experiments, exactly the same stimulus sequence was followed, and the same three observers served (the two experimenters and the 17-year old son of one). Data were collected in six separate sessions for each observer, and the data from the first session was discarded to minimize familiarization effects. Each session began with a block of 25 trials in which every orientation of the stimulus cube was presented once (and the canonical orientation twice). Then followed four blocks of 120 trials each, with each block including one presentation of each of the 120 different stimulus images (24 orientations x 5 stimulus keys). Each session took about 30-40 minutes, with no more than two sessions in a day, and at least 30 minutes break between sessions.

3.2 Results

Error rates were uniformly low: a total of 49 errors occurred in the 7200 trials consisting of sessions 2-6 for all three observers, yielding an overall rate of 0.68%. The

individual observers made 12, 29, and 11 errors, distributed roughly equally across the five last sessions (10, 11, 10, 12, and 6, respectively). Considering the pooled error data, 51% of the 49 errors were confusions between NEAR and FAR responses, that is, the responses that were associated with symmetry in the orientation cue. A further 35% could be accounted for by assuming the observer behaved as if the A was positioned with its feet against the near edge of the stimulus cube, as was the V, instead of the left edge. A further 8% were confusions between the responses that were distinguished by the asymmetric aspect of the cue, and the final 6% could have resulted from selecting the response that would have been pointed at by the apex of the V instead of the response that was pointed at by the apex of the A, and thus might constitute interference from the earlier tasks.

Two times were recorded for each trial. The reaction time began when the stimulus image was presented, and ended when the observer removed from the ready button the hand that then made the response. The movement time began with the release of the ready button and ended when the response button was pressed. Mean movement times, averaged across observers and sessions 2-6, are shown in Figure 5. The abscissa values represent rotations away from the head-on orientation. Thus, the canonical orientation is represented by the data points immediately to the right of the vertical dotted lines at zero rotation. Data points

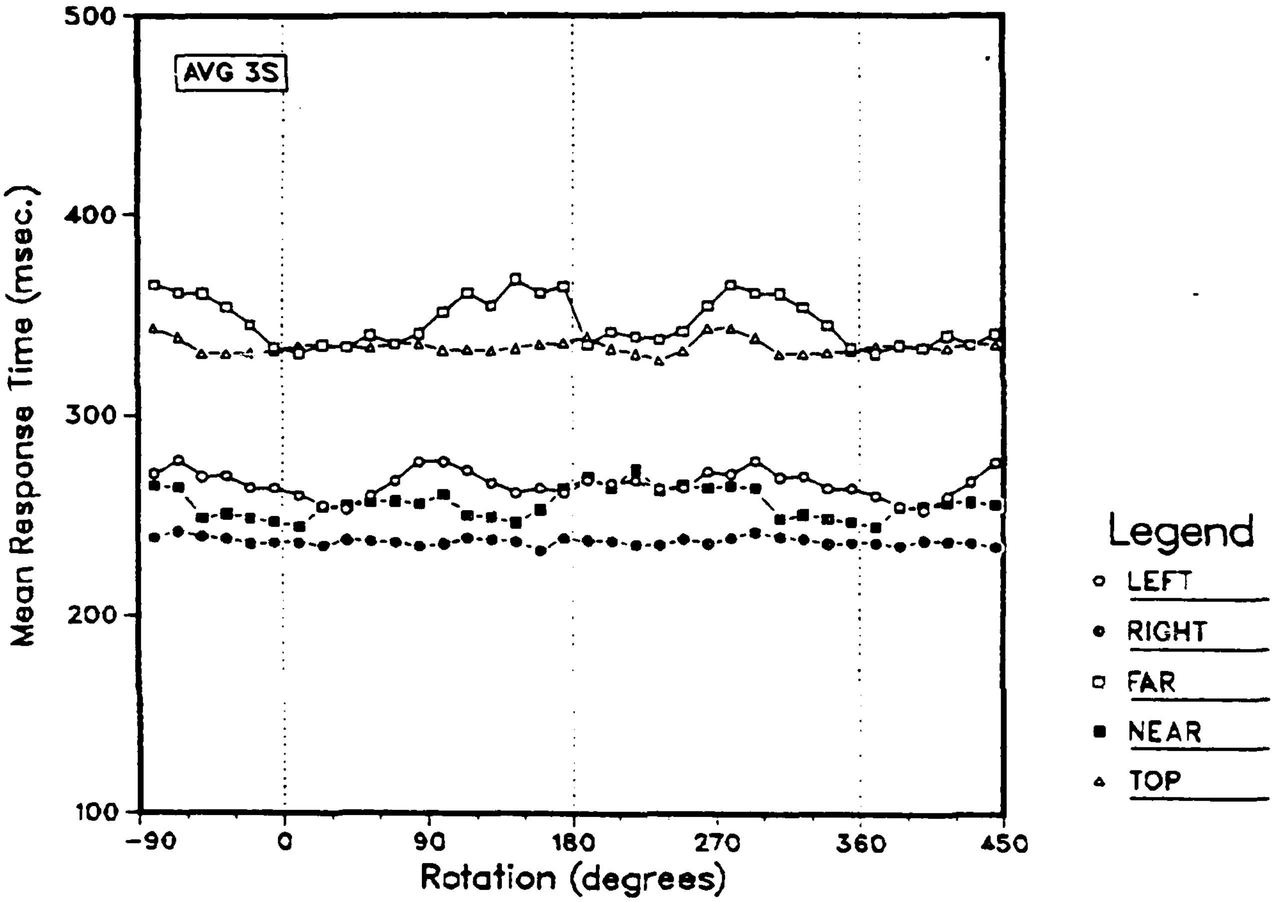

Figure 5. Mean movement times in the Y-axis task for each of the five response buttons, as a function of the orientation of the stimulus cube. The orientation cue was a capital A on the left edge of the bottom face.

for up to one quarter revolution in each direction from the head-on view are duplicated at the left and right sides of the plot, to emphasize the symmetry of the plots. As before, we applied

boxcar smoothing[1] to each point before plotting it, to reduce the noise in the plotted data.

As the figure shows, movement times were almost independent of cube orientation for the TOP, LEFT and RIGHT responses. Those for the NEAR and FAR responses showed some "leakage" from the peaks that appear in the reaction times for these responses in Figure 6 below. This leakage was due to the observers occasionally releasing the ready buttons to make a response, and then realizing that an incorrect response had been selected. The extra time needed to reselect the correct response was unavoidably included in the movement time for these trials.

Mean reaction times pooled across observers are plotted for each of the five responses as a function of stimulus cube orientation in Figure 6. As in the earlier experiments, the results obtained from the three individual observers were highly similar, differing only in detail, which argues that the results were not biassed by the two observers who were also experimenters. The results can be described in terms of the three strategies proposed to account for the results of the first

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[1] In boxcar smoothing, a plotted point represents the average of the true data point for that abscissa value with the two immediately adjacent values.

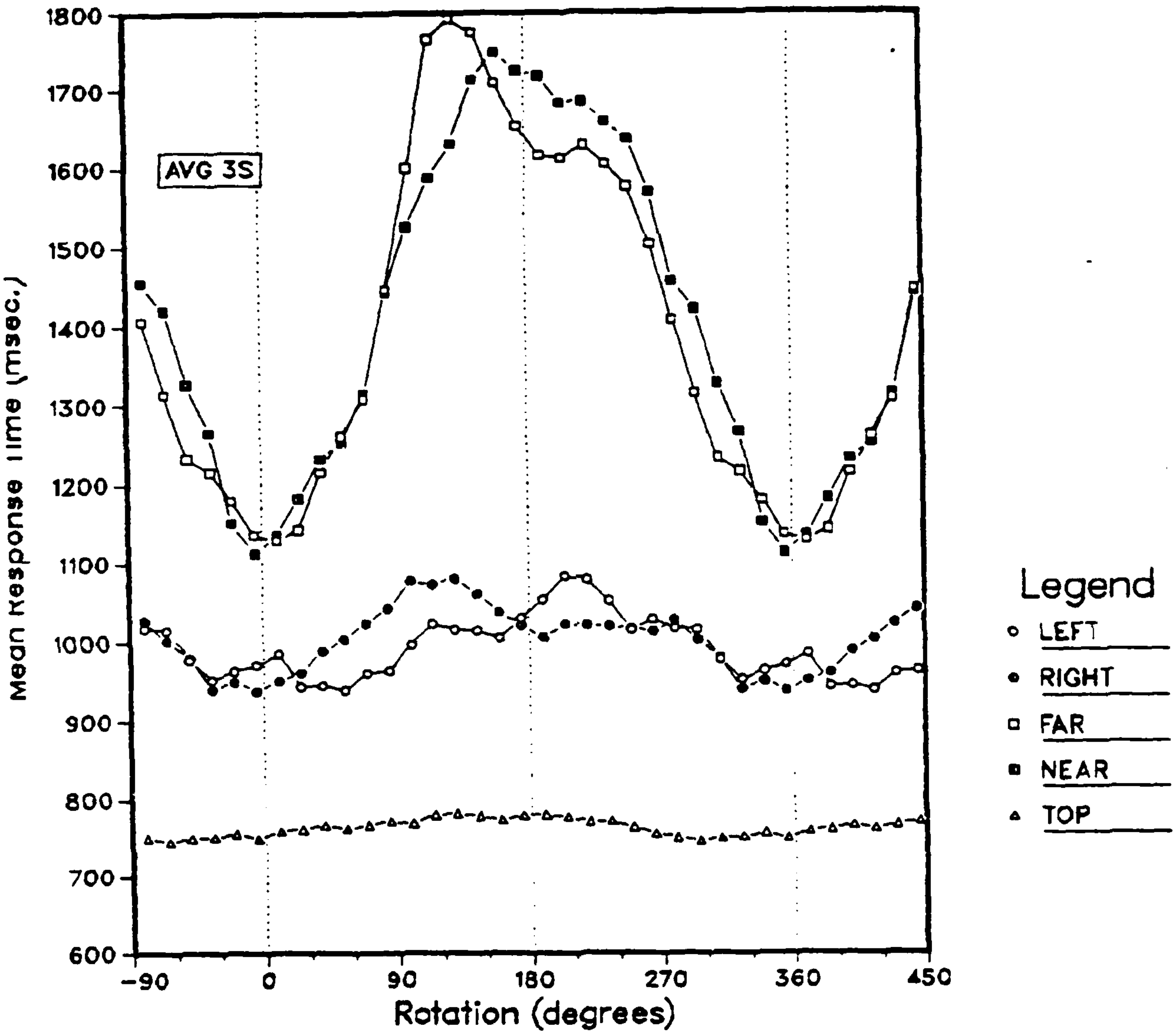

Figure 6. Mean reaction times, in the Y-axis task with the "A" orientation cue, for each of the five response buttons, as a function of the orientation of the stimulus cube.

set of experiments. Briefly, the reaction time function for the

TOP response was fast and flat, consistent with use of the Spatial strategy; those for the NEAR and FAR responses (associated with the symmetric aspect of the orientation cue, and therefore relying on the Rotational strategy) were peak-shaped; and those for the LEFT and RIGHT responses (associated with the asymmetric aspect of the orientation cue, and relying on the Relational strategy) were plateau-shaped.

The shapes of the three types of functions were quite similar in the present and the earlier experiments. To simplify these comparisons, Figure 7 reproduces the plotted data from Experiment 1 of our earlier report (Huggins & Getty, 1981). The earlier experiment was identical in every respect to the present one except for the orientation cue, which was a "V" with its apex towards the front edge of the bottom face in Experiment 1, instead of the "A" with its feet on the left edge of the bottom face in Experiment 5. Comparison of Figures 6 and 7 shows the similarity of:

- the functions for the TOP response;
- the functions associated with the asymmetric aspect of each cue (LEFT and RIGHT functions in Figure 6 and NEAR and FAR functions in Figure 7);
- the functions associated with the symmetric aspect of each cue (NEAR and FAR functions in Figure 6 and LEFT and RIGHT functions in Figure 7).

As predicted, the asymmetric position and shape of the A

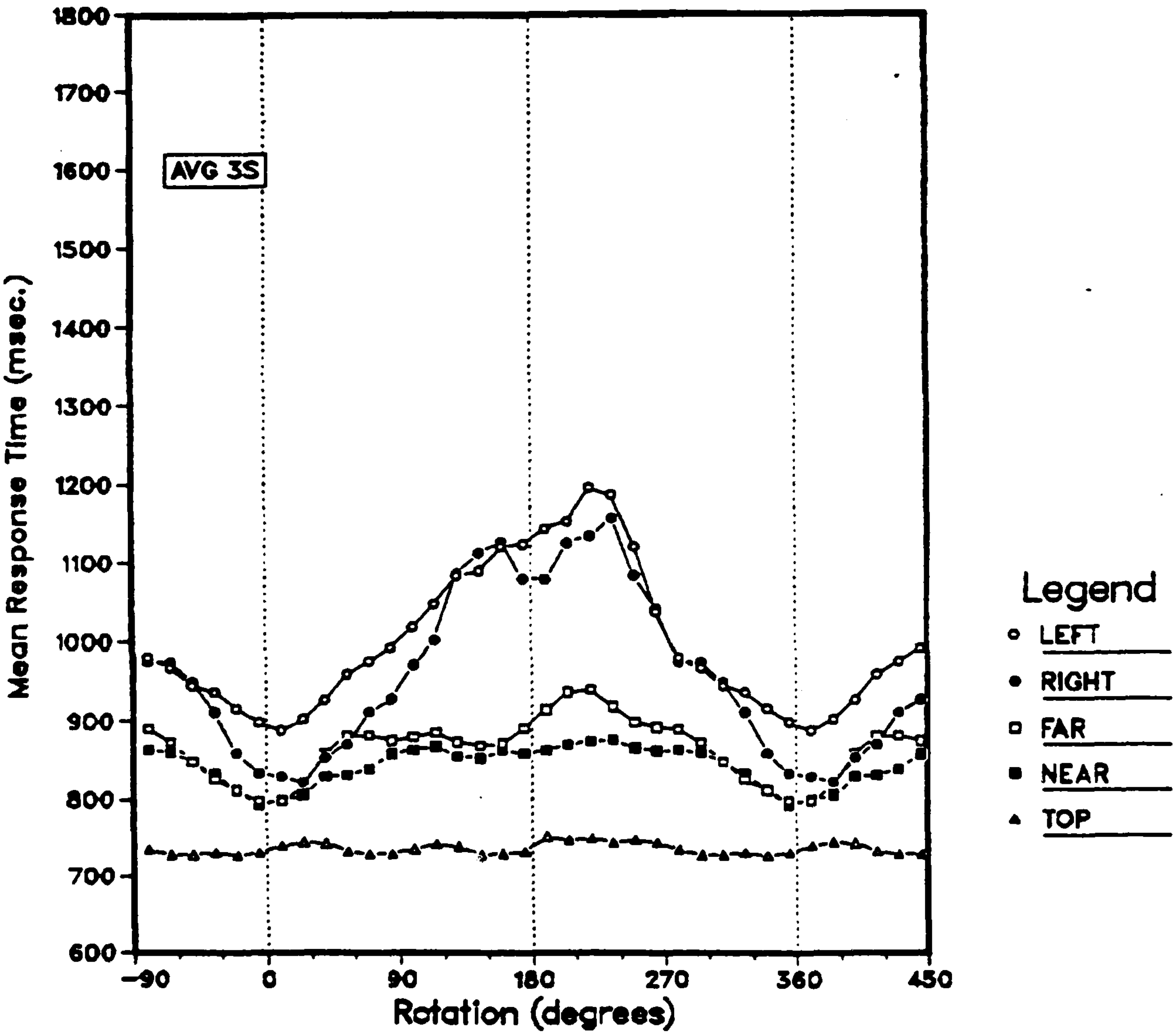

Figure 7. Mean reaction times in the Y-axis task with the "V" orientation cue reproduced from (Huggins & Getty, 1981), for each of the five response buttons, as a function of the orientation of the stimulus cube.

with respect to the LEFT and RIGHT stimulus keys made it easy to

distinguish between these responses, since observers were able to use a relational strategy. The LEFT and RIGHT reaction time functions show plateaus similar to those in the NEAR and FAR functions in Experiment 1. On the other hand, the NEAR and FAR stimulus keys could not be distinguished on the basis of the asymmetry of either the position or the shape of the A. Observers were consequently forced to adopt a Rotational strategy, which resulted in reaction time functions that were sharply peaked at the half-rotation orientations. Thus changing the orientation cue from a V on the bottom face pointing at the cube's front edge into an A on the bottom face standing on the cube's left edge reversed the types of function associated with the LEFT/RIGHT and the NEAR/FAR pairs of responses.

A second aspect of the results that deserves comment is the difference in duration of the reaction times associated with the "V" and with the "A." The smallest difference is for the TOP response, which took about 740 ms with the V cue and about 765 ms with the A cue. The fact that the difference is small is not surprising, since use of the Spatial strategy meant that the orientation cue was not needed for selecting this response. However, the fact that the TOP response was slower in Experiment 5 than in Experiment 1 conflicts with the expectation that learning would occur, shortening response times. The longer responses must either result from a context effect due to the

increased difficulty of the task as a whole, or must indicate that the orientation cue is not totally ignored while the Spatial strategy is being applied.

The plateau shaped functions ranged from 790 to 940 ms with the V, but from 930 to 1080 ms with the A, and the peak-shaped functions ranged from 820 to 1200 ms with the V, but from 1120 to 1800 with the A. The most likely explanation for this difference is that the A standing on the left edge of the bottom face of the cube was a less natural way of marking the cube's orientation than was the V touching the near edge. The fact that both pairs of functions are affected suggests that more is involved than just rotation of the cube to an awkward end-point. In addition, it is easier and more natural to remember that the apex of the V "points" towards the observer and therefore the NEAR face, than it is to remember that the apex of the A points towards the RIGHT face. Second, the observers apparently did not rotate their viewpoint so that the A appeared upright, and then translate the responses by 90 degrees, since this would have produced minima at 90 degrees rather than at the head-on orientation.

In summary, the results support the explanations offered for the findings of Experiments 1-4, and demonstrate that it should be possible to design an orientation cue that avoids the need for operators to rely on the Rotational strategy.

4. EXPERIMENT 6

The results of the first four experiments showed that using the forward-pointing V as orientation cue led to relatively fast response selection of the NEAR and FAR responses, and those of Experiment 5 just described showed similarly fast response times for the LEFT and RIGHT responses using the right-pointing A as orientation cue. The purpose of Experiment 6 was to attempt to combine these two sets of results, and obtain fast reaction times on all four responses.

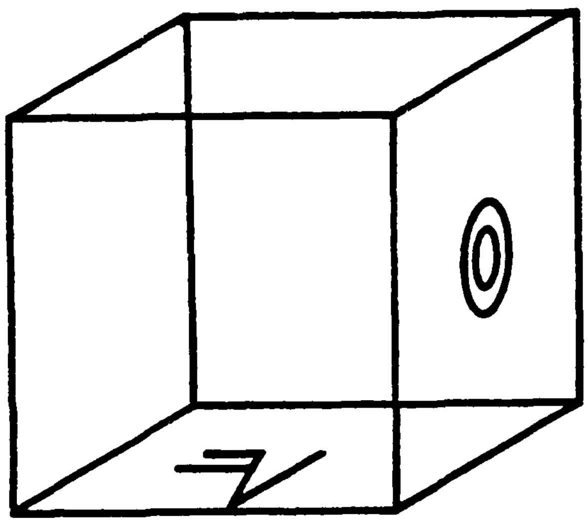

Figure 8. Schematic diagram of the stimulus cube for a typical trial in Experiment 6. The orientation cue was a capital letter V oriented as in the first four experiments, but with an extra serif attached to the top of its left upright.

Since the faster (plateau-shaped) response times appear to be associated with the asymmetric axis of the orientation cue, in Experiment 6 the cue was made asymmetric in shape relative to both pairs of responses. A modified letter V was used, drawn on the bottom face of the stimulus cube with its apex almost touching the front edge as before, but with an additional double cross-bar or serif added at the top and to the left of the left arm of the V, as illustrated schematically in Figure 8. The V was used as the basis for the new cue, rather than the A, because the overall response times associated with the V were faster than those associated with the A, presumably because the V positioned with its apex almost touching the front face of the cube was a more natural orientation cue (i.e. nearer to the population stereotype).

The serif made the V left/right asymmetric as well as up/down asymmetric. The serif pointed towards the LEFT key and away from the RIGHT key, and as before the apex of the V pointed towards the NEAR key and away from the FAR key. The same procedure was followed as before, with the stimulus cube appearing in 24 orientations constituting a revolution about the vertical Y-axis, and the same three observers served. As before, data was collected for six sessions, of which the first was discarded to eliminate familiarization effects.

4.1 Results

A total of 27 errors were made during the 7200 trials of sessions two to six (10, 11, and 6, by each of the three observers), for an overall rate of 0.38%. Fourteen of the errors were LEFT/RIGHT confusions, with 11 being a RIGHT response to a LEFT stimulus. It is possible that having the serif on the V pointing to the left stimulus key was contrary to the population stereotype (that is, fewer errors might have been made had the serif pointed at the right stimulus key). The decision to place the serif on the left arm of the V was made because the LEFT responses were slower, on average, than the RIGHT responses in the initial four experiments, and we thought that pointing the serif at the key yielding the slower responses might yield the greater overall gain in response time (see further under Experiment 8, below). However, the frequency of errors is really too small to justify such conclusions.

Movement time functions for the five responses are shown in Figure 9. Except for a small amount of leakage from the LEFT decisions (perhaps due to the reason just suggested), the functions contain no surprises.

The reaction time functions for each of the five responses are shown in Figure 10. The response function for the TOP

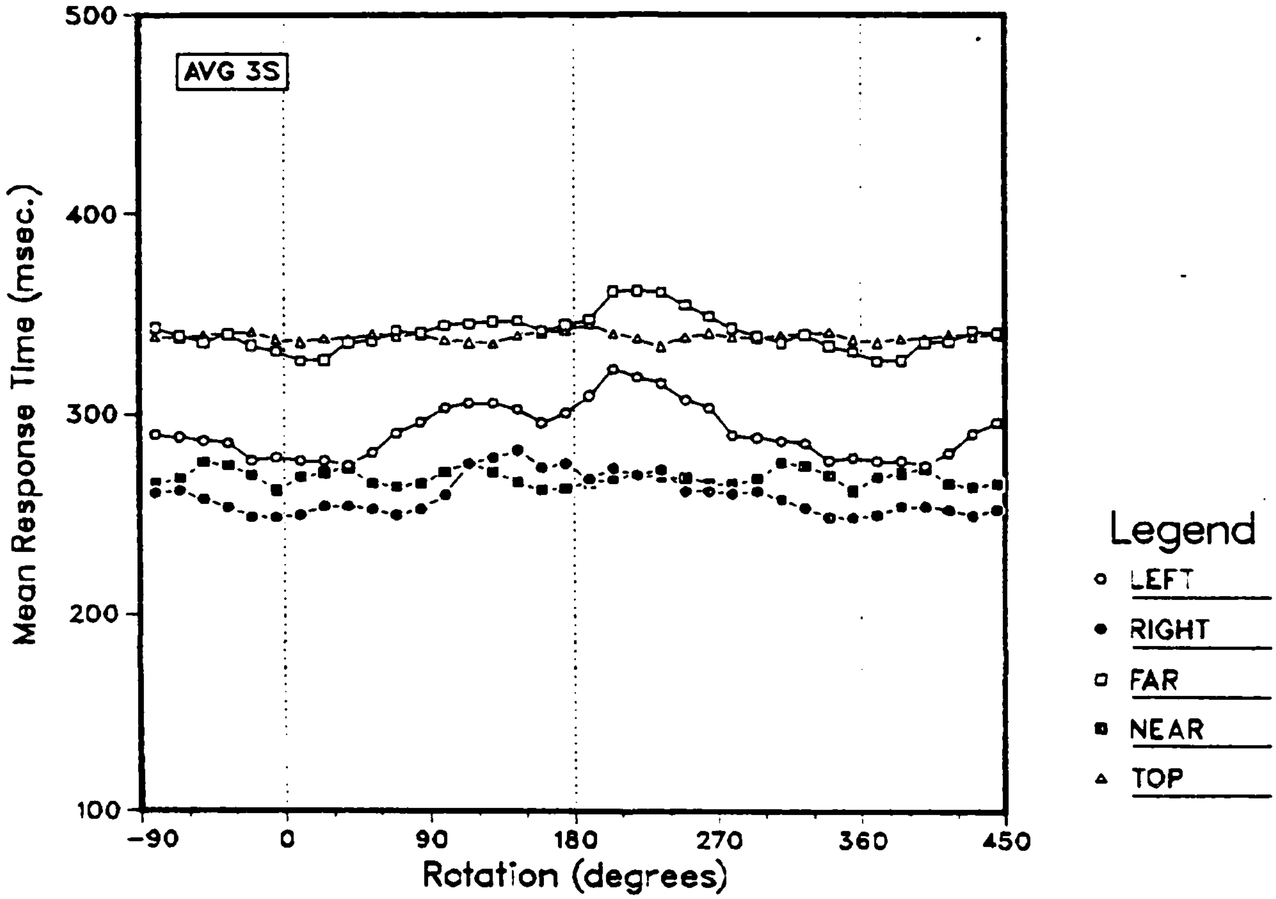

Figure 9. Mean movement times in the Y-axis task for each of the five response buttons, as a function of the orientation of the stimulus cube. The orientation cue was an asymmetric V on the near edge of the bottom face.

response is fast and flat, as expected. All four of the remaining responses yielded relatively flat plateau-shaped functions, consonant with our expectation that observers would be

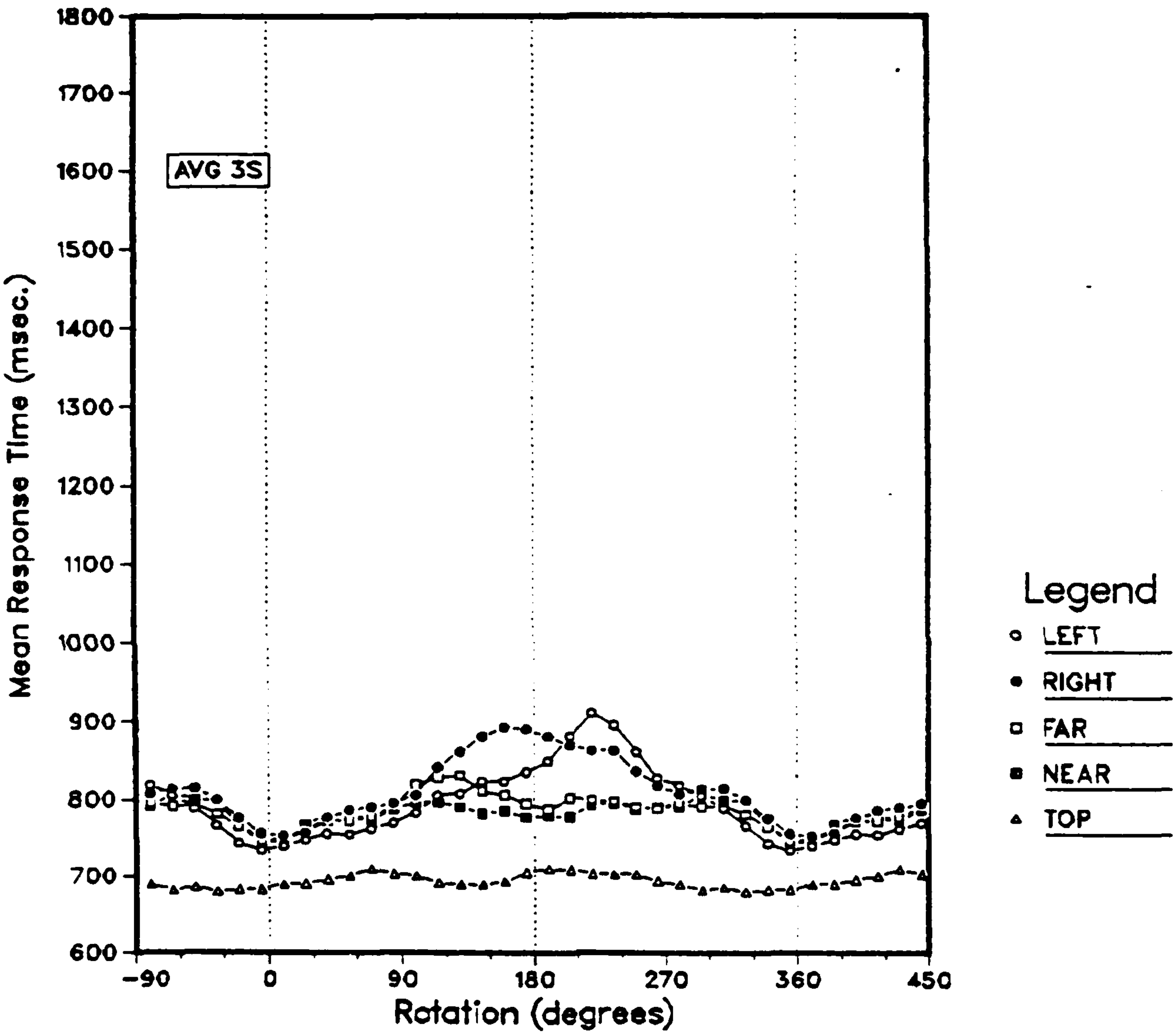

Figure 10. Mean reaction times in the Y-axis task for each of the five response buttons, as a function of the orientation of the stimulus cube, using an asymmetric capital V almost touching the front edge of the bottom face as orientation cue.

able to use the relatively efficient Relational strategy. The

large peaks associated with use of the Rotational strategy have almost disappeared.

A second noticeable aspect of the results is that the response times typical of each of the four plateau-shaped functions are appreciably shorter than in any of the earlier experiments. A possible reason for this is that the number of different strategies the observer must keep in mind is lower in the present experiment, since none of the responses depended on use of the Rotational strategy. As a result, the decision logic required by the task is simpler than in earlier studies.

A second possible explanation for both the minor remaining peaks in the LEFT and RIGHT functions, and for the improved performance throughout, is that the only difference between Experiment 1 of the initial set and the present Experiment 6 can be ascribed to learning. By the time observers reached the start of the sixth experiment in the series, they had accumulated a total of over sixteen thousand trials, more than half concerning rotations about the Y-axis. Although we cannot rule out this explanation with the data at hand, it does seem unlikely. For one thing, learning should also have showed its effects in Experiment 5 above, which it clearly did not, since response times were uniformly longer in this experiment than in Experiment 1 of the initial set (compare Figures 6 and 7). Explanations in terms of learning will be discussed further below.

The results demonstrate that elimination of inappropriate cue symmetry can avoid the need for the observer to make use of the inefficient Rotational strategy, with substantial performance benefits. However, even with this improvement the plateau-shaped response functions lie above the function for the TOP response, with the implication that the Spatial strategy yields the best performance of all.

5. EXPERIMENT 7

The task used in Experiment 6 to demonstrate the effectiveness of making the orientation cue asymmetric was both the easiest and the most practiced of the tasks in Experiments 1-4. To rule out the possibility that the improvement found was due solely to extended practice, we decided to use the new cue again in a replication of the most difficult task in the first set (Experiment 4), in which rotations about any one of the three axes might occur unpredictably on a given trial. In Experiment 7, the same orientation cue was used as in Experiment 6: the V with the serif attached to the left upright, drawn on the bottom face of the cube with its apex almost touching the front edge.

A total of 22 orientations were presented, consisting of the canonical orientation, and seven rotations away from the canonical orientation in 45 degree steps about each of the cube's three axes. That is, every third orientation was used from each of the Y-axis, Z-axis, and X-axis series, with the replications of the canonical orientation omitted. The images are illustrated in Figure 11, except that the serif does not appear on the V. (The figure is, in fact, a negative print of a paste-up of Polaroid prints taken of the actual display during the initial set of experiments, a tedious procedure we did not wish to repeat.) The 24 images are arranged as three blocks of eight,

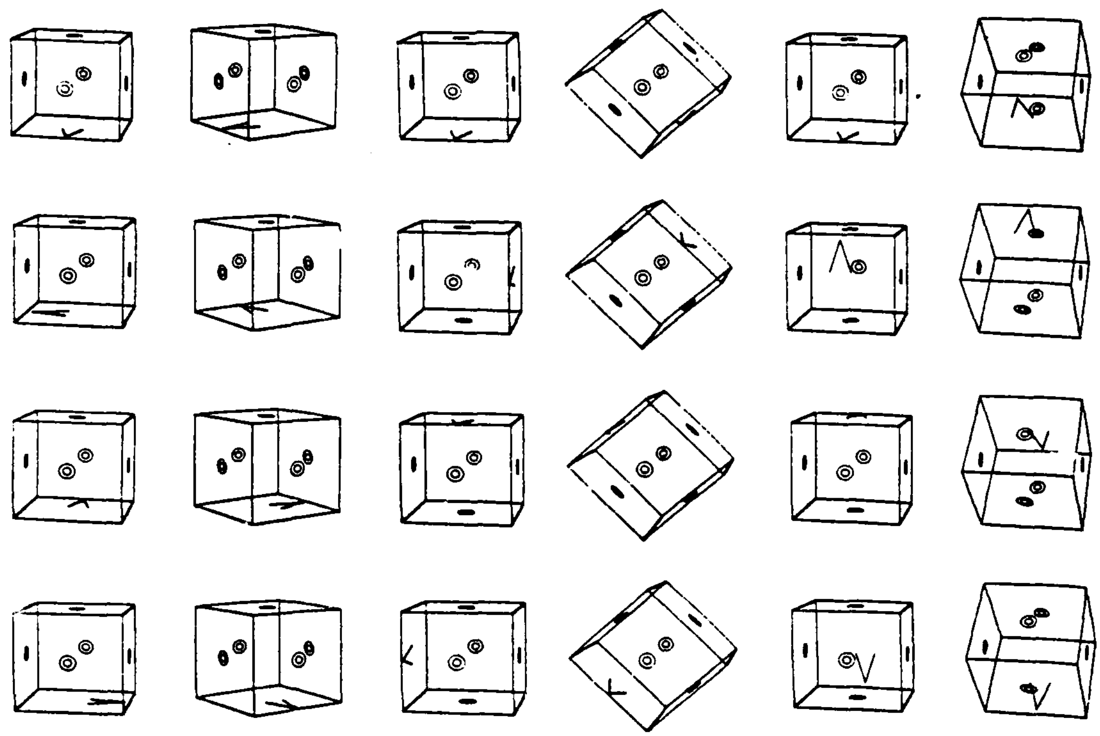

Figure 11. The 22 orientations used in Experiment 7 are shown, with two exceptions: the serif does not appear on the orientation cue, a V, and each image shows all five response keys, whereas the observer never saw more than one on any trial. The left eight images comprise the Y-axis rotation (to be read row by row); the middle eight images comprise the Z-axis rotation; and the right eight images comprise the X-axis rotation. The canonical orientation that appears as the upper left image in each block was included once only.

the left eight (to be read two at a time, row by row) show the rotation about the Y-axis; the middle eight about the Z-axis; and the right-hand eight about the X-axis. The canonical orientation

appears as the upper left member in each block of eight, but was only included once, yielding 22 different orientations. For economy, each orientation also shows all five stimulus keys, whereas observers saw only one key on any trial.

The same procedure was followed as before, except that each block of trials during an experimental session contained 110 trials (22 orientations x 5 responses) instead of the 120 trials of the single-axis experiments. The same three observers served as before, for six experimental sessions, of which the first was discarded to reduce familiarization effects.

5.1 Results

A total of 35 errors were made out of the total 6600 trials in sessions two to six, yielding an overall error rate of 0.53%. Individual observers made 10, 10, and 15 errors, respectively. LEFT/RIGHT confusions accounted for 66% of the errors, with two-thirds of these being LEFT responses to RIGHT stimuli. Again there is a hint that the asymmetric cue would be more natural if the serif pointed to the right rather than to the left. NEAR/FAR confusions accounted for only 11% of the errors; and the TOP stimulus produced a NEAR/FAR response in 20%.

The results are shown in Figure 12 (solid points and lines) where they are compared with the results obtained in the earlier identical experiment with the symmetric cue, the V without attached serifs (dotted points and lines, from Experiment 4 in (Huggins & Getty, 1981)). Each data point represents a total of about 60 judgments (errors were not replaced), 20 from each of the three observers. Note that the data points here were <u>not</u> submitted to boxcar averaging. The results show that the dramatic peaks in the reaction time functions found with the symmetric cue have largely disappeared. The peaks in Experiment 4 occurred at orientations 180 degrees away from the canonical orientation, where with the symmetric cue it was necessary to decide which axis the rotation had taken place about in order to choose between the LEFT and RIGHT response. Adding the serif to make the cue asymmetric removed this necessity, with a corresponding dramatic improvement of response times.

Except for these data points close to the 180 degree orientation, the shapes of the two functions in each panel are quite similar, although almost all the data points for the V with the serif lie below those for the symmetrical V. The fact that the shapes are similar may mean that the remaining difficulties, especially with the Z-axis and the X-axis stimuli, lie in finding and interpreting the orientation cue -- this was clearly harder to see in some of these orientations (see Figure 11), and the

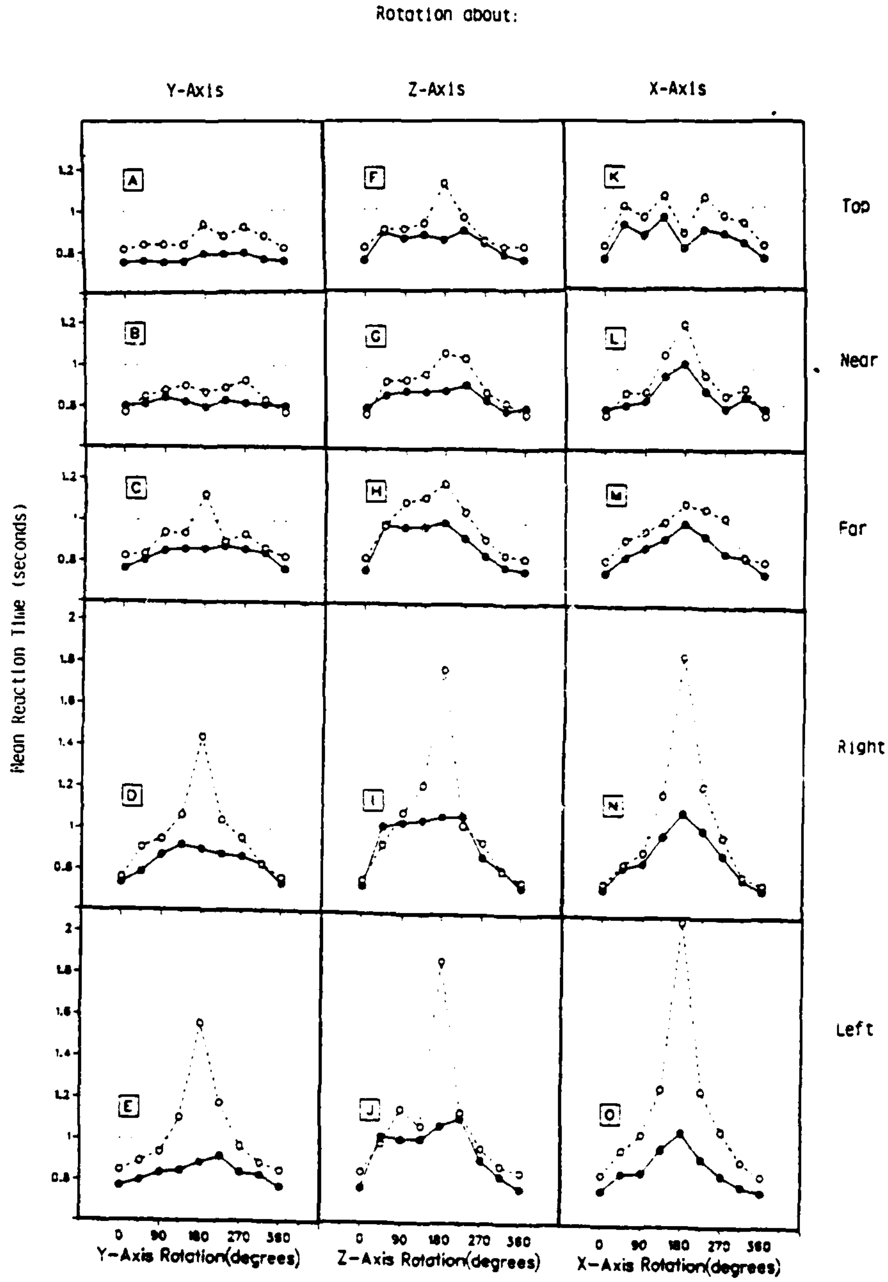

Figure 12. Reaction times are compared, separately for each response (rows) and for rotation about each axis (columns), between responses made using the asymmetric V (solid points) and those made using the symmetric V (open points, from Experiment 4 (Huggins & Getty, 1981).

difference in level between the pairs of functions may indicate the superiority of the asymmetric cue. On the other hand, the similarity of shape and difference in level may indicate that the asymmetric cue was not particularly superior in these remaining orientations. Rather, learning had taken place, and this had the effect of flattening the functions without greatly changing their shape. Against the learning explanation is the fact that some data points, especially those in panels I and J (RIGHT and LEFT responses, Z-axis rotation) showed little or no improvement, contrary to what would be expected if learning had occurred. One would expect some effects of learning to be apparent in all the panels. In either event, the asymmetric cue clearly produced major performance improvements where uncertainty was present, at the reversed orientations. Furthermore, each observer reported finding the task much easier when the serif was present.

A further set of interesting comparisons can be made between reaction time using the V-with-the-serif and mixed axes of rotation, and the "pure-axis" rotations in Experiments 1-3 of the initial set, in which rotations about only one axis occurred in each experiment. Under the pure-axis conditions, observers could use strategies that took advantage of the single axis: in particular, they could use the Spatial strategy for responding when the stimulus key lay on the axis of rotation (i.e. TOP response for rotation about the Y-axis, NEAR and FAR responses

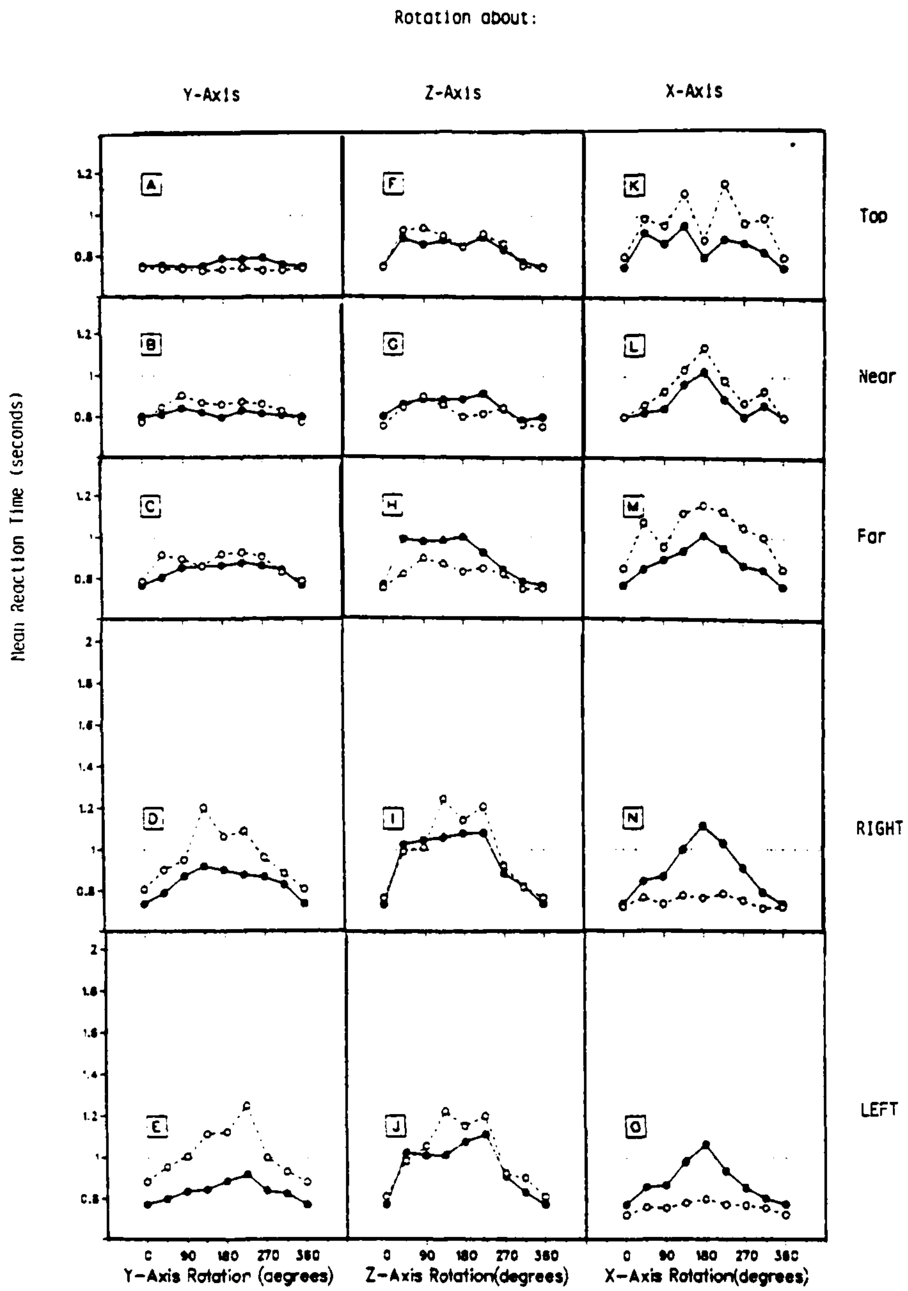

Figure 13. Reaction times with the asymmetric V (solid points) are compared with those with the symmetric V in Experiments 1-3 (open points), in which rotations were about the Y-, Z-, and X-axes respectively.

for rotation about the depth or Z-axis, and LEFT and RIGHT responses for rotation about the lateral X-axis). The data from Experiment 7 are compared with the Y-, Z-, and X-axis data from the initial set of experiments in Figure 13, using the same format as Figure 12. The solid points and lines again show the data for Experiment 7, with mixed axes and the asymmetric V-with-serif, and the open points and dotted lines show the data from the pure-axis rotation experiments with the symmetric V (no boxcar smoothing applied).

Inspection of the fifteen panels in Figure 13 show that in only four panels was performance clearly better in the pure axis experiments (panels A, H, N and O), and one further panel where it was marginally better (G). These five panels correspond exactly to the conditions in which observers were able to use the Spatial strategy in the pure axis condition. When rotation was about the Y-axis, the TOP stimulus key lay on the rotation axis and therefore its position was invariant across all the orientations presented in the experiment, and similarly for the NEAR and FAR keys in the Z-axis experiment, and for the LEFT and RIGHT keys in the X-axis experiment. The fact that "pure" performance is better than that with the asymmetric cue in the Z-axis case (panels G and H) is particularly interesting. We were not willing to conclude from the results of the earlier study that observers had used the Spatial strategy for the NEAR and FAR

responses, although these keys lay on the rotation axis, because the data did not exactly fit our requirements for implicating the Spatial strategy, which specified that the function should be fast and <u>flat</u>, showing no effects due to changes in orientation. This latter requirement was only approximately fulfilled. The present result, that performance was faster in the pure-axis tasks if and only if the key lay on the rotation axis, suggests that the Spatial strategy was indeed used, in which case the effects of orientation (minor peaks at 90 and at 270 degree orientations) can perhaps be ascribed to variation in the visibility of the V with rotation.

Two further observations should be made about Figure 13. Since rotations could occur unpredictably about any of the three axes in this experiment, the Spatial strategy could not be used at all except perhaps close to the head-on orientation. Since the orientation cue was asymmetric with respect to both LEFT/RIGHT and to NEAR/FAR stimulus key pairs, and the TOP key always appeared on the face opposite to the V, Relational strategies were available for all five responses. Why then are there consistent differences in the shapes of the functions depending on which axis was used for rotation? In general, rotations about the Y-axis yielded functions that were flat or slightly bowed upwards; rotations about the Z-axis yielded functions that were sharply plateau shaped, with asymmetric

skirts; and rotations about the X-axis gave functions that were peaked -- except for the TOP response, which had subsidiary minima at about 90 and 180 degrees. The subsidiary minima can probably be accounted for because the TOP response was called for whenever the stimulus key appeared on the face <u>opposite</u> to the face bearing the orientation cue, and it was <u>not</u> necessary to decide which of the opposing faces bore the V and which the stimulus key. The fact that they were on opposed faces uniquely specified the TOP response. This argument may also apply to Z-axis rotation, for the TOP response only.

To return to the shape differences: the main differences between rotations about the three axes concern the range of positions and orientations taken by the orientation cue. When rotation was about the Y-axis, the <u>position</u> of the orientation cue was highly predictable, although its <u>orientation</u> was not. Thus the observer had no difficulty finding the cue, just interpreting it. The situation was different when rotation was about the Z-axis. Now the <u>position</u> of the cue was uncertain, since it could appear anywhere round the outside of the image, but its orientation, when found, was predictable: it always pointed towards the observer. Rotation about the X-axis was hardest of all, because both the position and the orientation of the cue were unpredictable, although correlated. Thus, peak shaped functions result whenever the orientation of the cue is

unpredictable, suggesting that some sort of rotational process may be necessary to establish the orientation of the cue.

The asymmetry in the skirts of the Z-axis function is probably the result of variation in the visibility of the orientation cue. As mentioned elsewhere, the canonical orientation of the cube was rotated 10 degrees forwards, to compensate for the 10 degree declination of the observer's view below the horizontal (this made the cube's vertical Y-axis coincide with the real-world vertical), and 10 degrees clockwise looking down the Y-axis, so that none of the cube's edges would ever appear parallel to the virtual image of the CRT face (such lines are impossible to draw with SpaceGraph, since they require the CRT to be brightened at multiple X-Y positions exactly simultaneously). These tilts had the effect, at the 45 degree Z-axis rotation, of presenting the bottom face of the cube almost edge on, with the result that the orientation cue was much harder to see. In fact, the V was relatively easy to see in three of the Z-axis orientations presented in Experiment 7, and hard to see in the other five (see Figure 11), and these latter correspond exactly to the points with elevated response times in panels (F) G, H, I, and J.

A final point worth making is that the NEAR responses were always slightly faster than the FAR responses made under the same

conditions. This was probably due to the orientation cue being slightly more closely related to the NEAR stimulus key (the V's apex almost touched the front face of the cube) than to the FAR stimulus key (the top of the V's uprights only extended towards the back face as far as the middle of the bottom face). In conclusion, making the orientation cue asymmetric made a Relational strategy available for selection of each of the five responses, and this yielded substantial performance improvements even in the hardest of the experimental tasks used in the initial set of experiments.

6. EXPERIMENT 8

In the discussions of the results of Experiments 2 and 3, we mentioned the possibility that the improved performance relative to that obtained in the first and fourth experiments of the initial set, using the symmetric V as orientation cue, might be due to learning rather than the superiority of the asymmetric V-with-serif used in the later experiments. Although we presented evidence against the learning explanation, it seems reasonable to ask how much learning had, in fact, taken place over the course of the seven experiments.

Therefore, Experiment 8 replicated exactly Experiment 1, in which the orientation cue was a plain (i.e. left-right symmetric) letter V, and the cube was rotated about its vertical Y-axis. The stimuli used in Experiment 1 were shown above in Figures 2 and 3. The same three observers served for six experimental sessions, of which the first was discarded. Thus, Experiment 8 is an exact replication of the initial experiment, using the same observers and the same stimuli in the same sequence, performed approximately 11 months later and after 440-680 intervening trials <u>in each orientation</u> with identical or closely related stimuli.

6.1 Results

A total of 25 errors were made in the 7200 retained trials in Experiment 8, to yield an overall rate of 0.34%. This compares with 134 errors and a rate of 1.9% in Experiment 1. The individual observers made 5, 7, and 13 errors, compared with 21, 32, and 79 errors, respectively in the initial experiment -- the proportions are strikingly similar. Confusions between LEFT and RIGHT responses accounted for 64% of the errors, vs. 83% in the initial experiment. NEAR/FAR confusions accounted for 16% of the errors vs. 6% before. Quarter-revolution errors accounted for 16% vs. 11% before, and again these were all generated by the same single observer. Unfortunately, the frequencies are too small to make chi-squared comparisons meaningful. However, although the error rate has been cut by over 80%, the <u>distribution</u> of errors is similar, which suggests that the observers did not drastically change their strategies.

The mean reaction times for each of the five responses are shown as a function of orientation in Figure 14, which is plotted at the same scale as Figure 7, showing the comparable results for the initial experiment. Several conclusions can be drawn from the comparison of the figures. First, it is obvious that extensive learning has occurred. This is apparent in each of the five responses: typical TOP responses have shortened from about

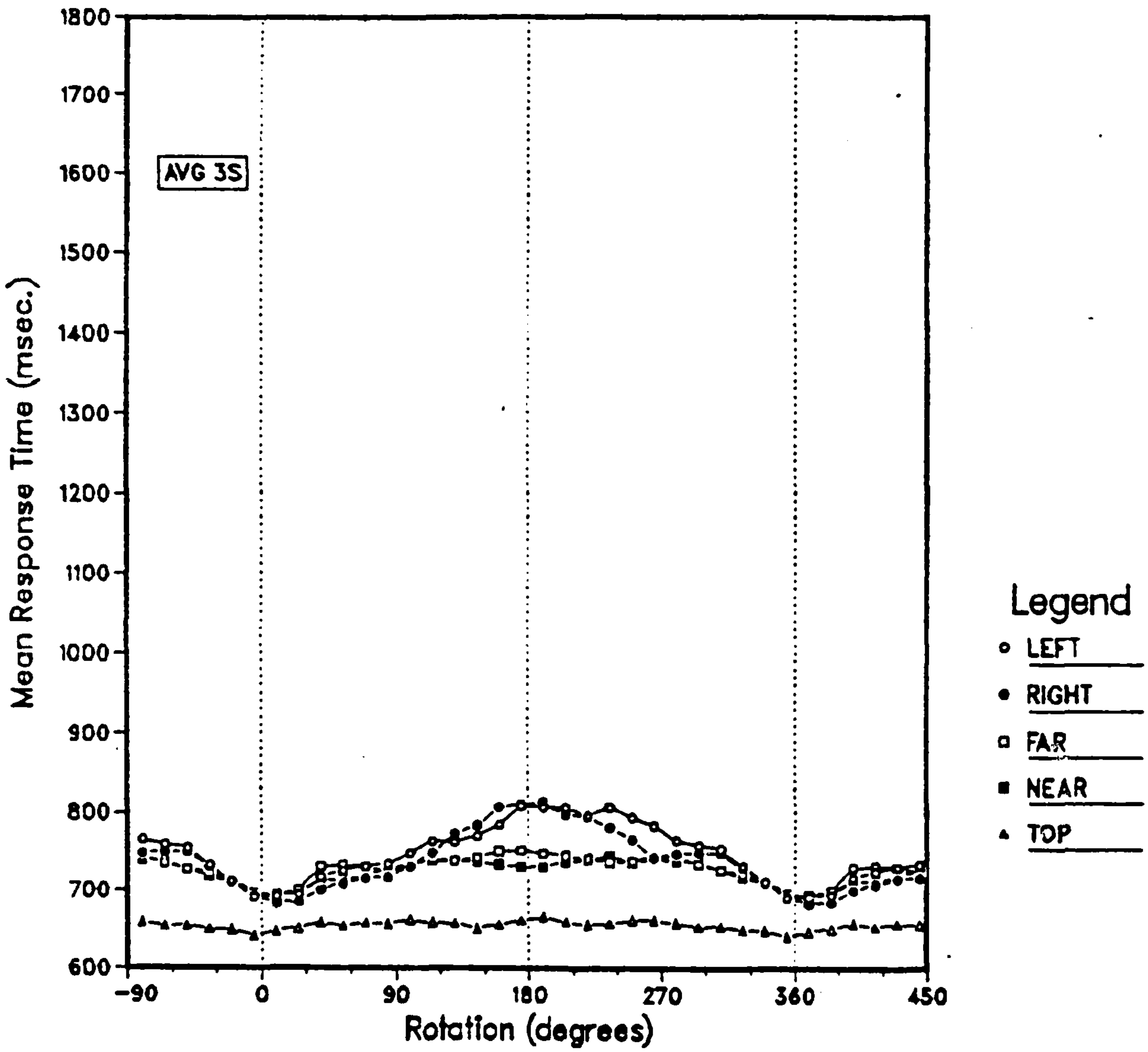

Figure 14. Mean reaction times in the Y-axis task for each of the five response buttons, as a function of the orientation of the stimulus cube, using the original symmetric capital V as orientation cue. The experiment was an exact replication of Experiment 1 (Huggins & Getty, 1981).

740 ms to about 650 ms; NEAR and FAR responses from 800-900 ms to

670-750 ms; and LEFT and RIGHT responses from 830-1200 ms to 680-800 ms. Second, the TOP responses are still appreciably faster and less influenced by orientation than are the other four responses, indicating that the Spatial strategy was still in use for this response, but for no other response. The functions for NEAR and FAR responses are still plateau-shaped, with skirts at the sides of the plateau sloping down to the minima at the head-on orientation. The LEFT and RIGHT functions are plateau-shaped, with superimposed peaks near to the reversed orientation. However, the magnitude of the peaks is greatly reduced relative to those in the initial experiment (see Figure 7).

The amount of improvement due to learning was much greater than expected. In fact, superficial comparison of Figure 14 with Figure 10 suggests that much of the improvement that we ascribed to use of the asymmetric cue in Experiment 6 could have been due to learning. To explore this question further, we compared in a single figure the progressive changes in mean response times over the three experiments that involved both rotation about the Y-axis only and used a V (symmetric or not) as the orientation cue, Experiments 1, 6, and 8. Figure 15 shows mean response times for each of the five responses, pooled over orientations and observers, as a function of the session number. Session numbers 1-5 represent the five sessions of retained data in Experiment 1, which used the symmetric V. Sessions 6-10 represent the

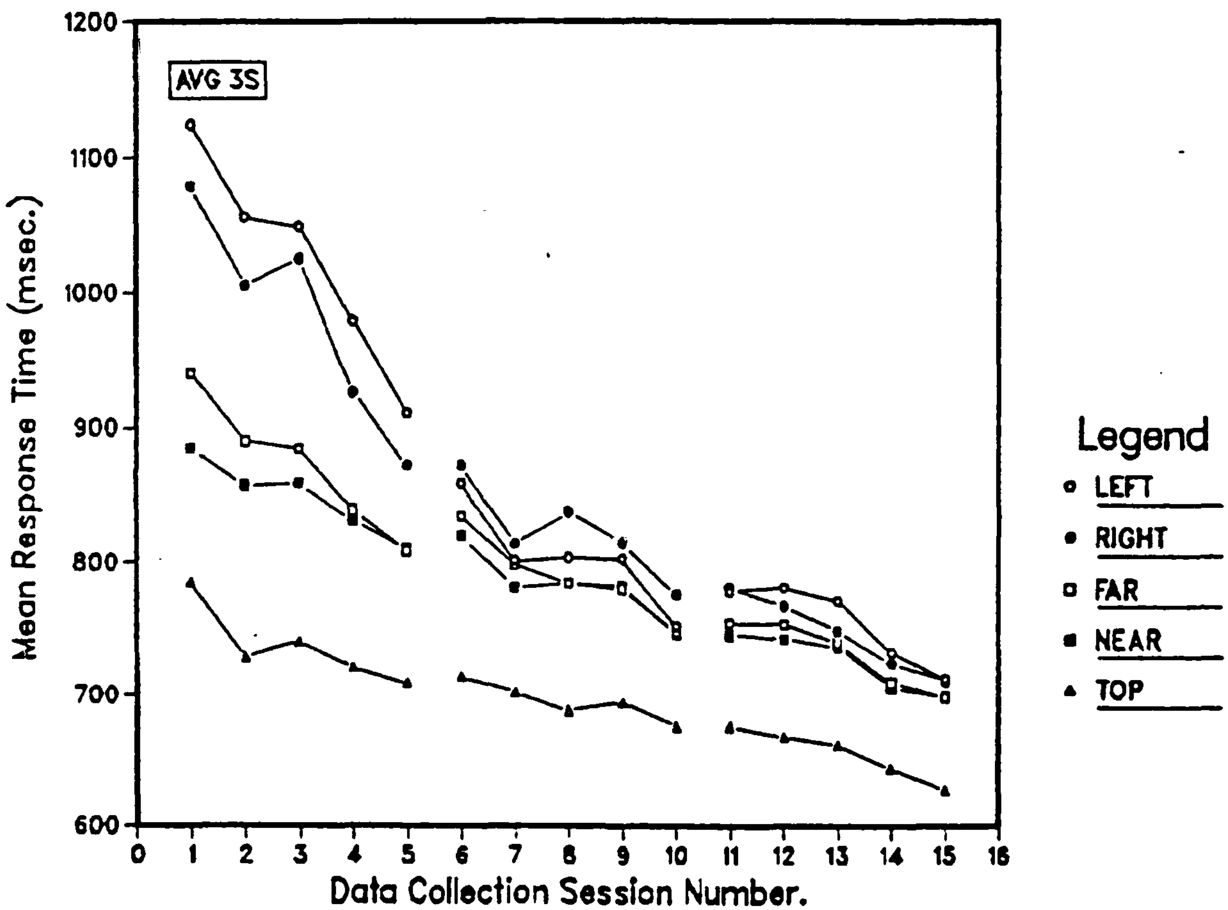

Figure 15. Mean reaction times for each of the five responses, pooled across observers and orientations, as a function of session number, for Experiment 1 (sessions 1-5), Experiment 6 (sessions 6-10), and Experiment 8 (sessions 11-15).

corresponding sessions for Experiment 6, which was identical

except that the asymmetric cue was used. Sessions 11-15 represent the corresponding sessions for Experiment 8, which used the symmetric V and was an exact replication of Experiment 1. The learning functions are plotted in three sections, since other exposure occurred during the gaps. For example, between sessions 5 and 6, each observer served for six sessions in each of four tasks: the Z-axis task, the X-axis task, and the mixed-axes task, all with the symmetric V orientation cue; and the Y-axis task using the differently oriented A as orientation cue. Between sessions 10 and 11, they served in the mixed-axis task with the asymmetric V. Each data point represents the mean of about 288 responses (3 observers x 4 blocks per session x 24 orientations, with errors not replaced).

At first glance, the curves presented in Figure 15 suggest that performance improved in an orderly way over the three experiments, with no significant changes in the middle experiment, with the asymmetric V. This result, again, was very surprising to us, since it was in direct conflict with our strong impression that adding the serif to the V made the task appreciably easier. However, closer inspection of Figure 15 shows that the serif did have a significant effect.

The addition of the serif was not expected to have an equal effect on all responses. It was not expected to have any effect

on the TOP response, since the Spatial strategy was used throughout for selecting this response. It was expected to have at most a small effect on the NEAR and FAR responses, since these responses were already selected with a Relational strategy that was not altered by addition of the serif. These responses might have been slightly speeded, since all responses except the TOP response were now selectable by a Relational strategy, and therefore it was necessary to choose between only two types of strategy, instead of between three. On the other hand, the responses might have been slightly slowed by the necessity of choosing between four different Relational strategies, instead of between only two. Addition of the serif should have had the largest effect on the LEFT and RIGHT responses -- especially the LEFT, since the serif pointed towards the left stimulus key and away from the right. Close inspection of the LEFT and RIGHT functions in Figure 15 shows some striking and consistent differences that strongly support our subjective impressions about the utility of the asymmetric cue. In Experiment 1 (sessions 1-5), the LEFT responses were slower than the RIGHT responses in every session, by 45, 51, 24, 53, and 39 ms, respectively. But in Experiment 6 with the asymmetric V (sessions 6-10), the LEFT responses were <u>faster</u> than the RIGHT responses in every session, by 13, 12, 34, 12, and 24 ms, respectively. This difference is highly significant (P=0.004 by

Fisher Exact Probabilities Test). In Experiment 8 with the symmetric V (sessions 11-15), the pattern reverts to that of the initial experiment, with the LEFT response being slower than the RIGHT in four of the five sessions, by -3, 14, 23, 8, and 2 ms, respectively. The difference between Experiments 6 and 8 (sessions 6-10 vs sessions 11-15) is also significant (P=0.024 by Fisher test).

Inspection of Figure 15 also suggests that the major effect of the serif was to improve LEFT response performance during Experiment 6, with a much smaller effect on the RIGHT response. As a result of the time interval and intervening exposure (some of it, perhaps, interfering) between sessions 5 and 6, response times for the TOP, NEAR, and FAR responses increased slightly (by 5, 10, and 24 ms, respectively), whereas those for the LEFT responses <u>decreased</u> by 52 ms, and those for the RIGHT responses were unchanged. Between sessions 10 and 11, the TOP response time was unchanged, the NEAR response was 1 ms faster, and the FAR response was 7 ms slower. The LEFT response was 26 ms slower, and the RIGHT response was 5 ms slower.

In summary, even though performance improved strikingly over the course of the eight experiments, and, indeed, has still not reached asymptote, there is evidence that adding the serif to the orientation cue improves performance even in the experienced

observer. In the naive observer the effects would probably be much larger, as can be deduced from the results of Experiment 7, in which the very large peaks in the LEFT and RIGHT responses with the symmetric V virtually disappeared when the serif was added to the V (see Figure 12). The addition of the serif might also be beneficial when the task must be performed under stress, and regression to an earlier mode of responding might be expected to occur (Bahrick, Noble, & Fitts, 1954; Fuchs, 1962).

7. CONCLUSIONS

The results demonstrate that display-control incompatibility can be reduced by appropriate coding of the orientation of objects within the display, and show that it is very important that any object presented in a 3-D display be asymmetric, to permit operators to determine orientation directly from the displayed object without having tc resort to the potentially slow and inaccurate rotational strategy. This conclusion is perhaps especially important because it is counterintuitive.

Across all experiments, the Spatial strategy consistently yielded the fastest responses whenever it could be applied. This suggests that in vehicle control or other similar displays where fast, accurate responses are at a premium, an inside-out view should be available to the operator if possible. This recommendation becomes increasingly important as the angular discrepancy between the two views increases, reaching its maximum when the operator views the controlled vehicle head-on rather than from behind. This degree of discrepancy is much larger than those considered by Roscoe in his discussion of inside versus outside view (Roscoe, 1968). However, the importance of inside view when the discrepancy is large is implicit in his Figure 2, showing a typical map-type navigation display that includes a switch that lets the pilot choose between a "north-up" and "heading-up" presentation.

Finally, we are impressed by the degree and duration of practice effects on reducing reaction times observed over the extended period of these experiments. It is clear in our results that (negatively accelerated) decreases in reaction times are found that extend over thousands of trials for each observer.

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